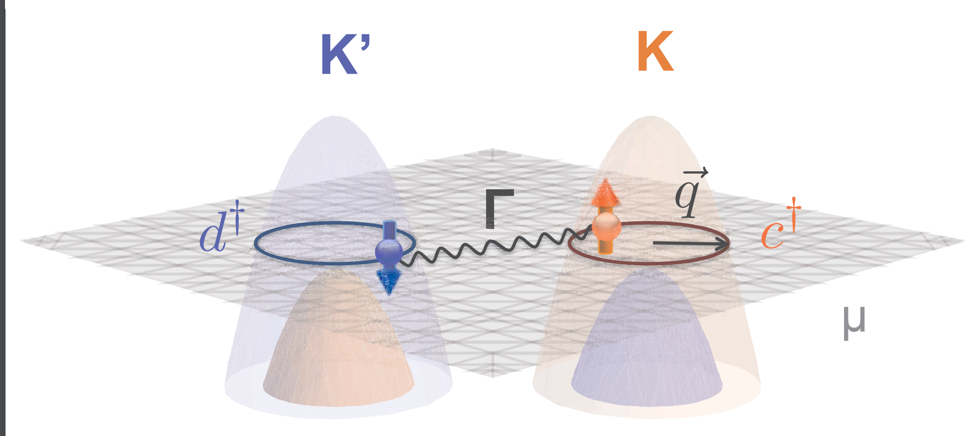
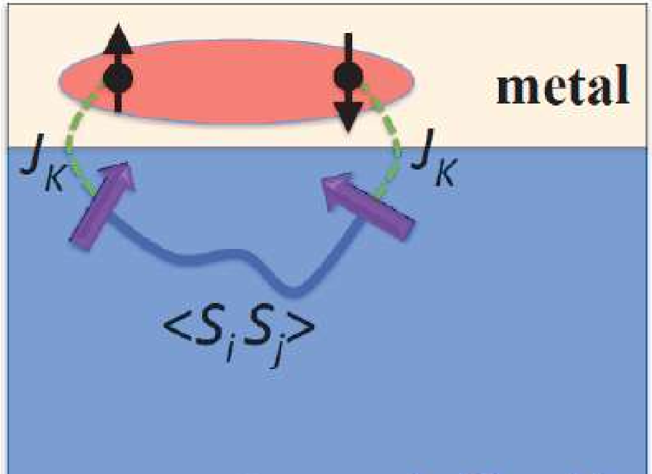
Let There Be Topological Superconductors



Nature Communications 8, 14985 (2017)



npj Quantum Materials 2 (1), 64 (2017)

Eun-Ah Kim (Cornell)

9.12.2019
Cabrera Summerschool

!! Wanted: Postdocs !!

Bethe/KIC Postdoctoral Fellowship in Theoretical Physics at Cornell's Laboratory of Atomic and Solid State Physics

Cornell University's Laboratory of Atomic and Solid State Physics is soliciting applications for the Bethe/KIC Postdoctoral Fellowship.

This prize fellowship will provide an outstanding theoretical physicist the opportunity to work with theorists and experimentalists in Cornell's physics department. Our group (www.lassp.cornell.edu/people/faculty) has broad interests in hard and soft condensed matter physics, including: cold atom physics, biophysics, statistical physics, hydrodynamics, electronic structure theory, materials science, strongly correlated electrons, nanoscience, computational physics and superconductivity. We also have growing efforts incorporating machine learning into studies of condensed matter physics.

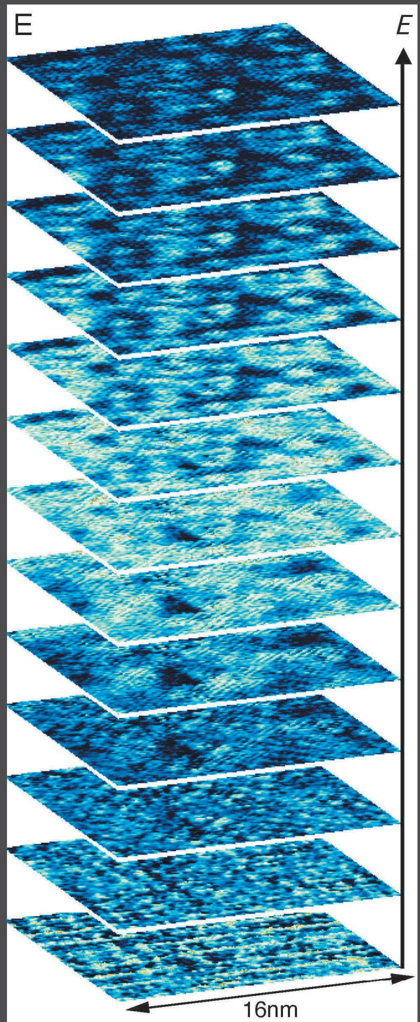
We actively encourage applications from diverse and historically underrepresented candidates.

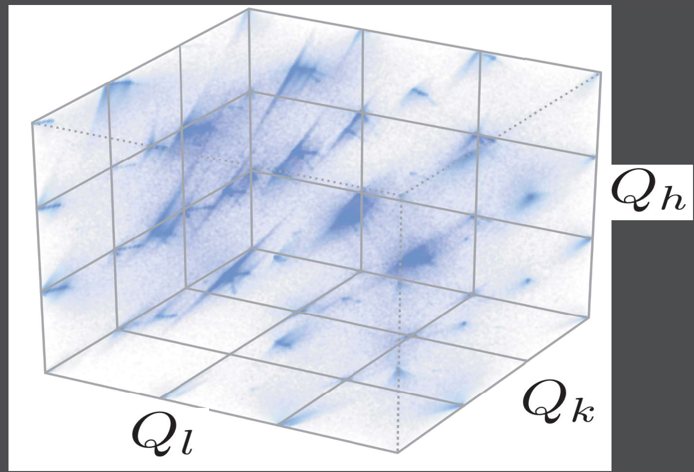
Please submit a CV, publication list, and a 1-3 page research statement to this website at **https://academicjobsonline.org/ajo/jobs/13989**.

https://academicjobsonline.org/ajo/jobs/13989

Navigating Data Driven Challenges using Machine Learning

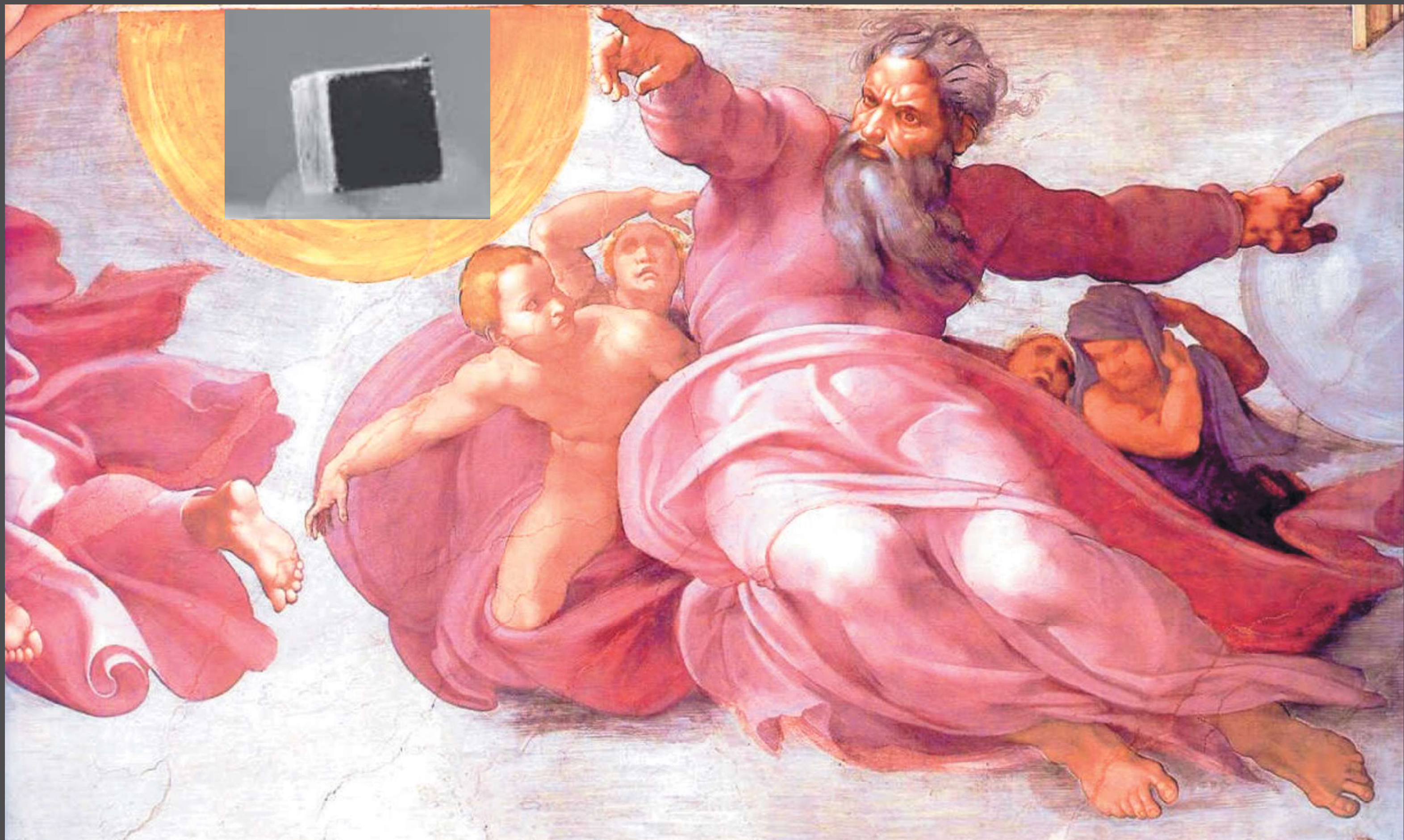
Many-body wave function





Position and Reciprocal Space Data

“Let there be a topological superconductor”…



Odd-parity Superconductors

are Topological
(host Majorana Zero Mode)

Review:
Kallin & Berlinsky, Rep. Prog, Phys. (2016),
Alicea, Rep. Prog. Phys (2012)

Majorana bound state in “spinless” SC

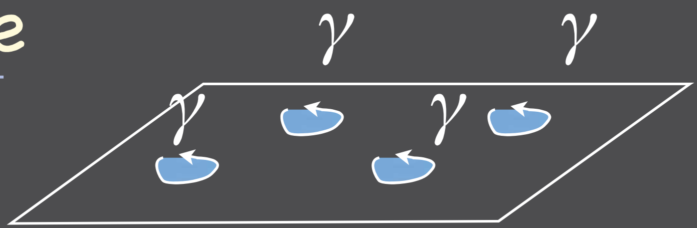
- Vortices of p+ip SF ➡ zero modes at the core

  Kopnin and Salomaa PRB (1991)

- Zero modes are Majorana
  - BdG qp’s $\gamma_i^\dagger = u\psi_i^\dagger + v\psi_i \quad \gamma_i^\dagger(E_n) = \gamma_i(-E_n)$
  - zero mode: $\gamma_i^\dagger(0) = \gamma_i(0)$

- Majorana + vortex composite

  ➡ non-Abelian Q-bits



Das Sarma, Tewari, Nayak (06) Stone & Chung(06) Ivanov(01)

Chung, Bluhm, EAK (07)

3D v.s.2D

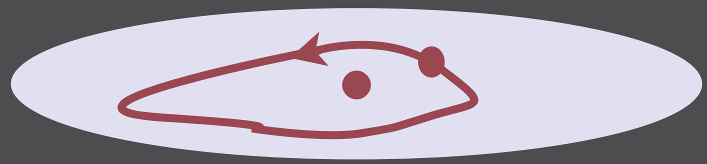
- Statistical angle (topological spin)

$$\psi\,(r_1,r_2) = e^{i\theta}\ \psi\,(r_2,r_1)$$

- 3D

  - double exchange $= I$
  - $\theta = 0$ (boson), π (fermion)

- 2D

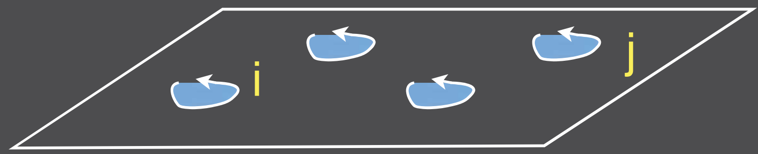


  - θ can be arbitrary
  - (abelian) Anyon

A pair of MBS = Q-bit

- The "fusion" rule and Q-bits

$$c = \gamma_i + i\gamma_j$$
$$c^\dagger = \gamma_i - i\gamma_j$$



: each pair of MBS host a two-state system

- 2n MBS's

$N_{2n}=2^{n-1}$ dimensional Hilbert space

Non-Abelian Statistics: Gates

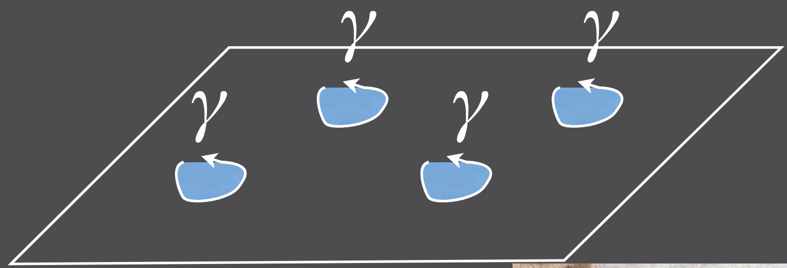
- n- nonabelian qp state ⇨set of Q-bits

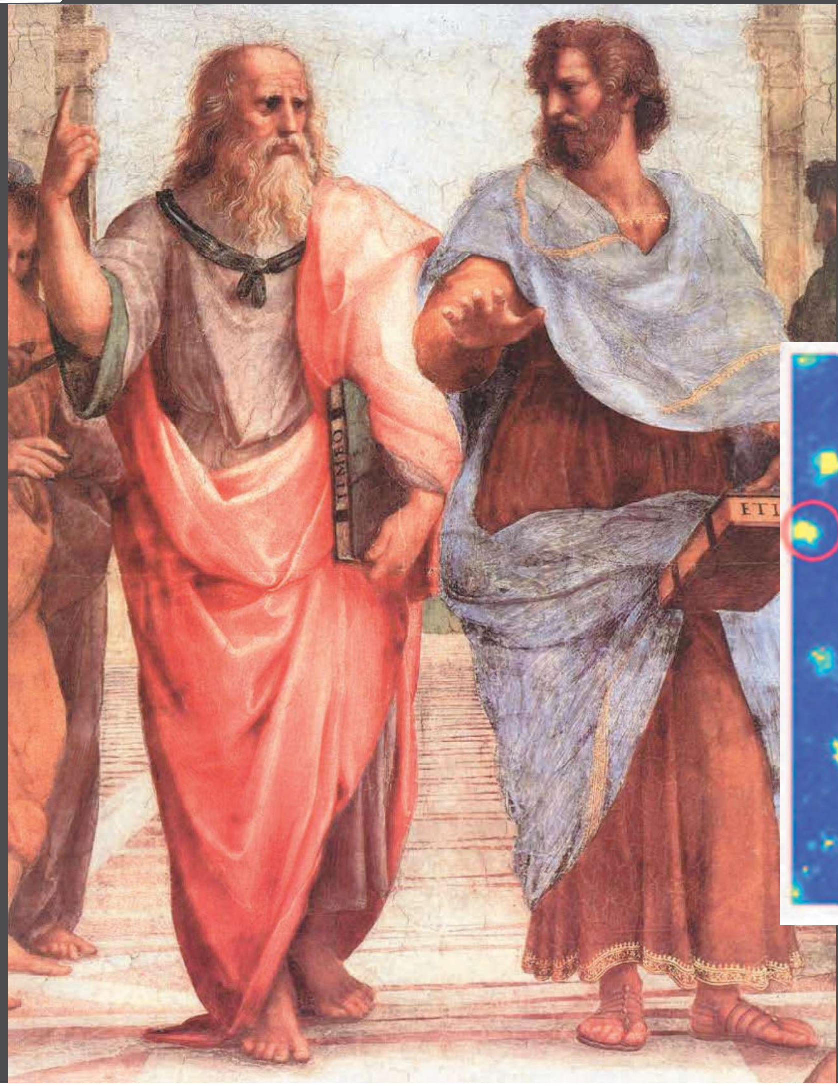
$$\Psi(x_1, \cdots, x_n) = \begin{pmatrix} \psi_1 \\ \vdots \\ \psi_{d(n)} \end{pmatrix}$$

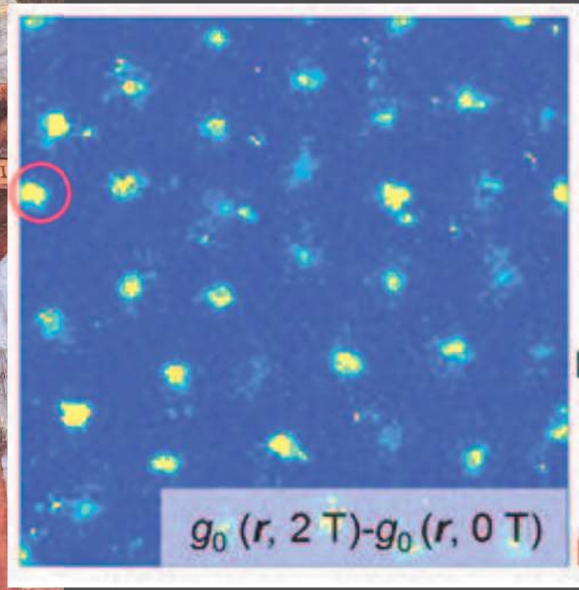
→ exchange of qp's: rotation in *d(n)* dim Hilbert space

$$\Psi(x_1 \leftrightarrow x_3) = M\Psi(x_1, \cdots, x_n)$$

$$\Psi(x_1 \leftrightarrow x_2) = N\Psi(x_1, \cdots, x_n)$$



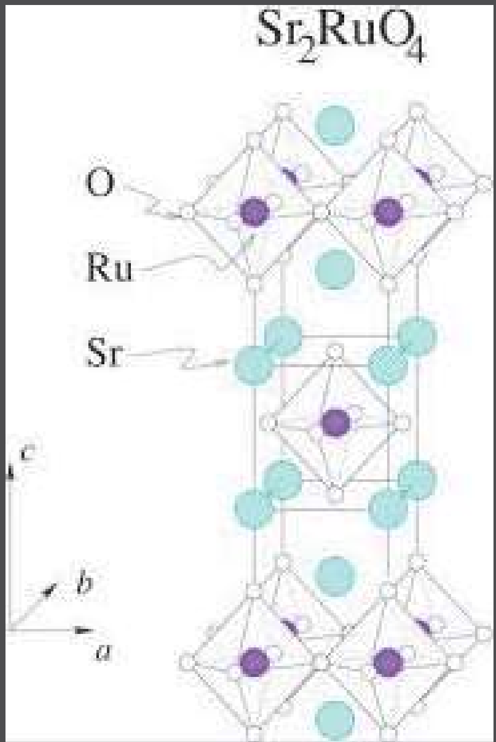




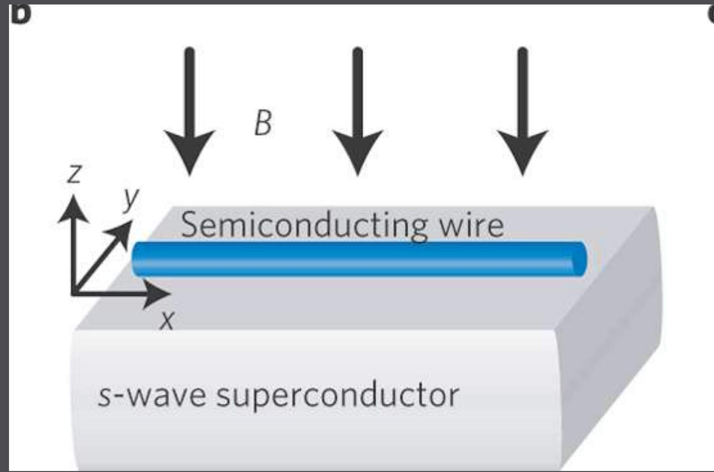
Hai-Hu Wen et al
(1909.01686)

Q. Topological Superconductor material?

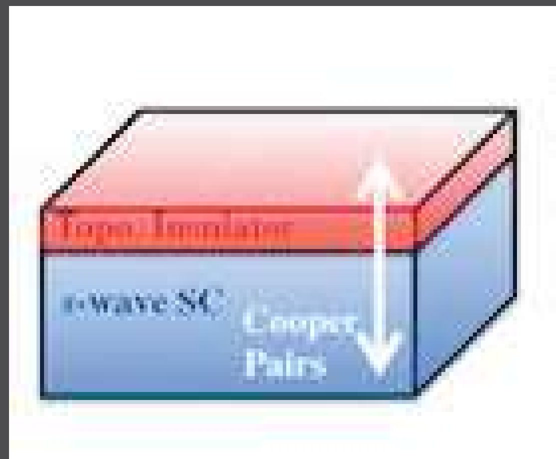
Bulk



1D proximity



2D proximity?



Review:
Kallin & Berlinsky, Rep. Prog, Phys. (2016),
Alicea, Rep. Prog. Phys (2012)

Designing 2D topological SC's

- 2D topological SC
  - odd-parity SC of spinless fermions
  - Majorana bound state

- Strategies:

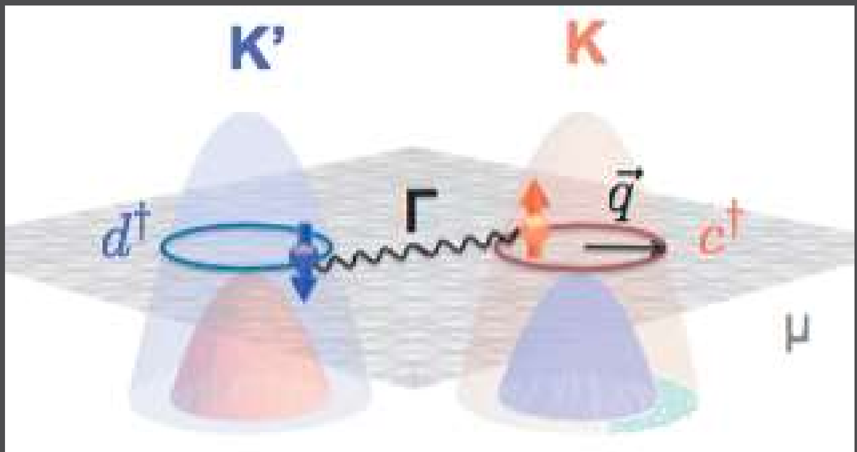
1) spinlessness

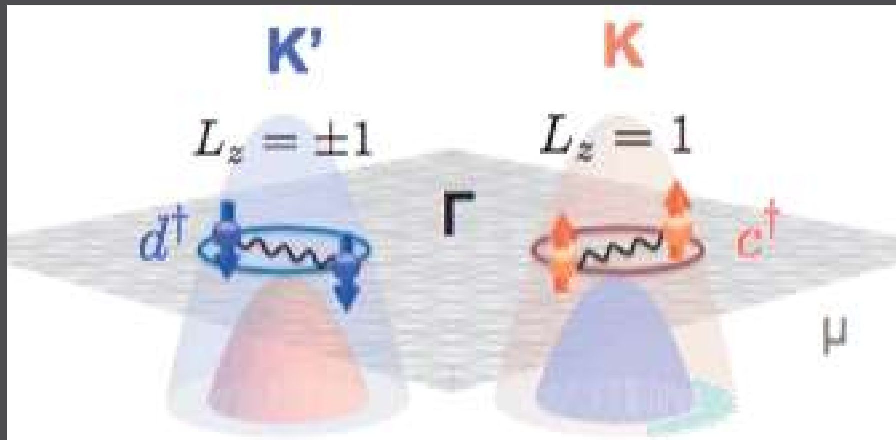
2) interaction

Strategy I

Manipulate the band structure

Topological superconductivity in group-VI TMDs





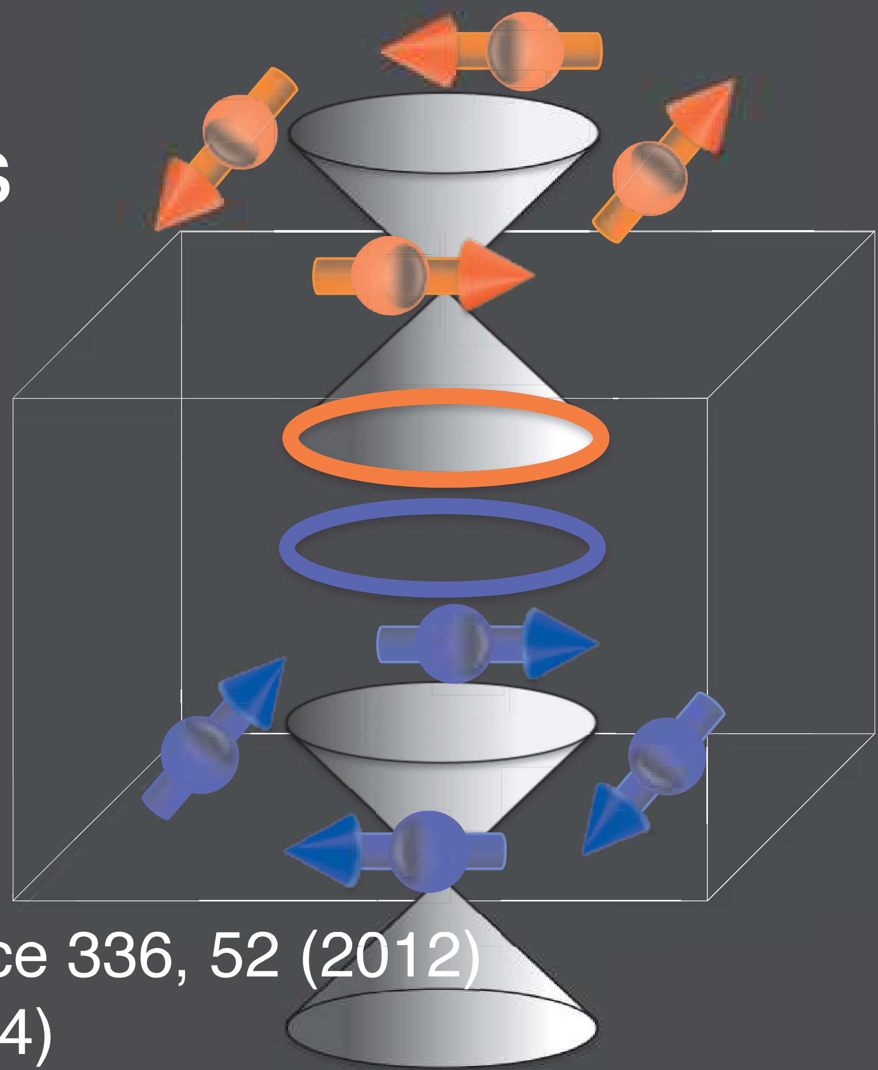
Yi-Ting Hsu, Abolhassan Vaezi, Mark Fischer, E-AK (Nature Communications 8, 14985 (2017))

Yi-Ting Hsu

Abolhassan Vaezi

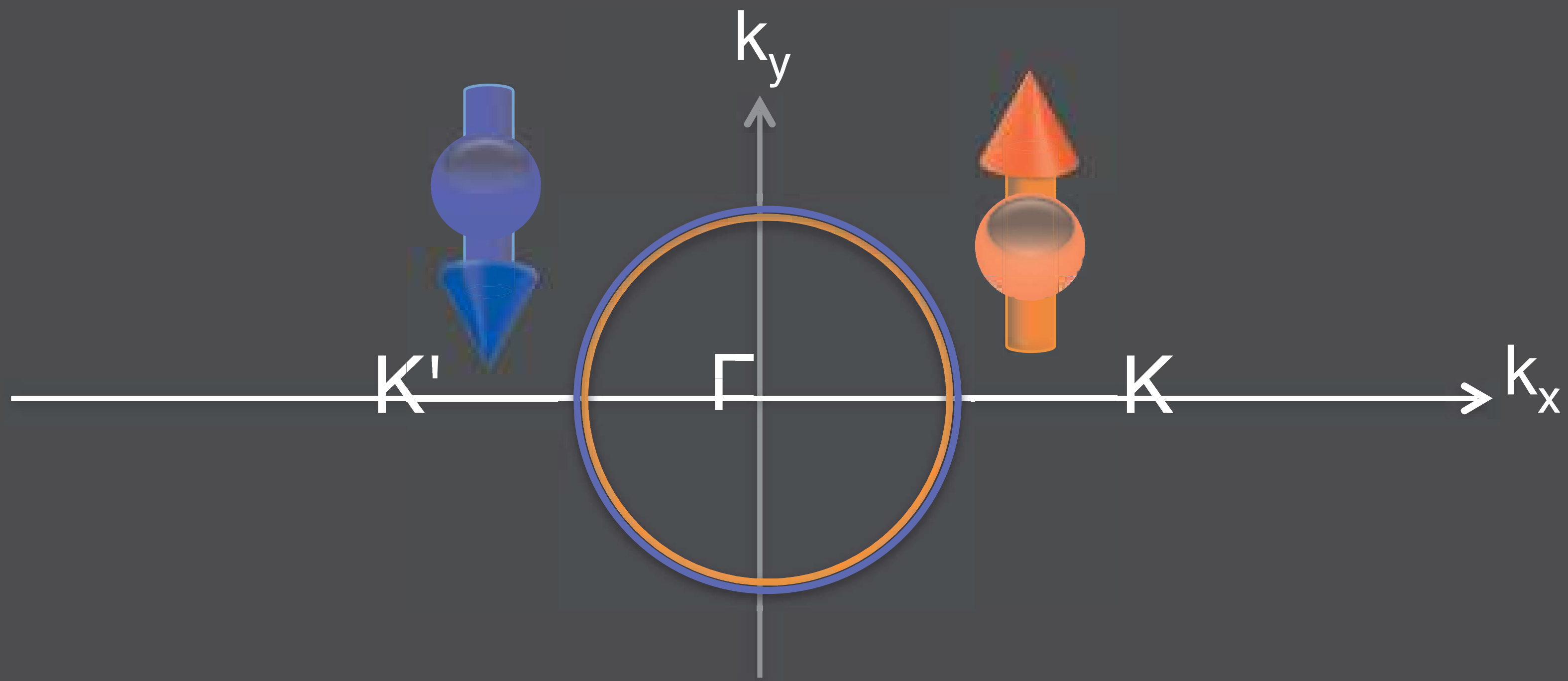
Spinless fermion via real space splitting

- TI surface states
- Proximity induce topo SC



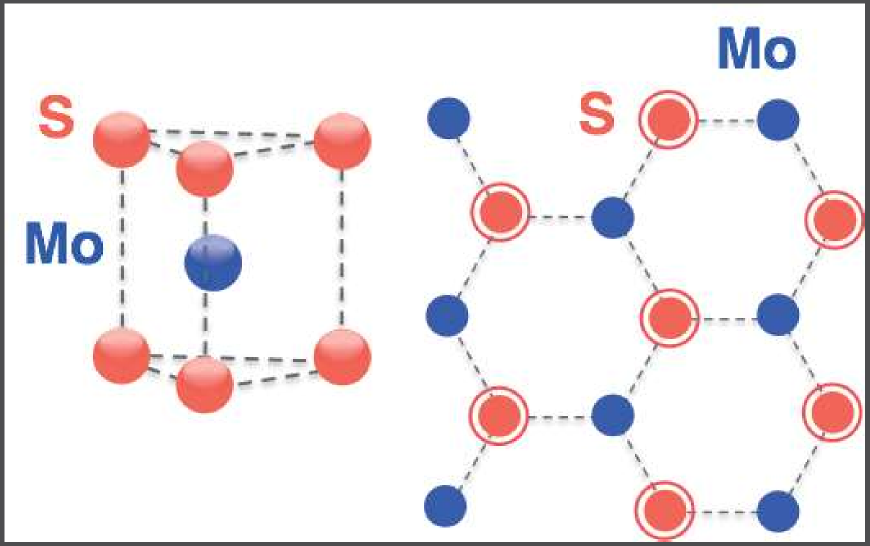
Fu & Kane, PRL (2008)
Experiments: Wang et al Science 336, 52 (2012)
Xu et al, Nat.Phys 10, 943 (2014)

Spinless fermion via k-space splitting?



Monolayer group VI TMD's

MoS_2, WS_2, $MoSe_2$, WSe_2



- Non-centro symmetric

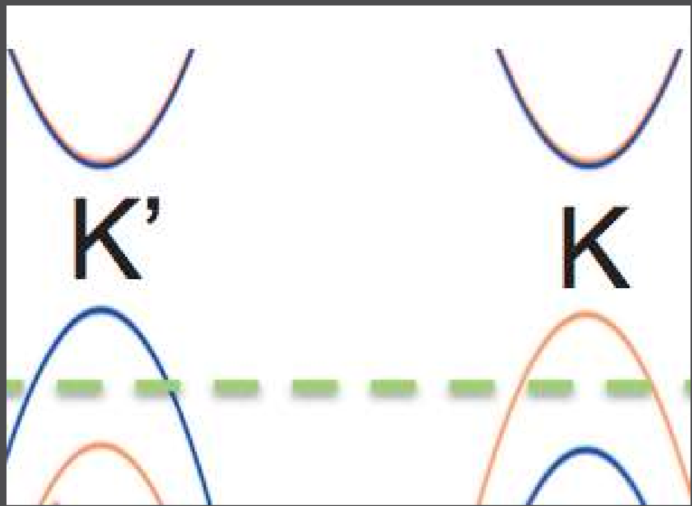
➡ Direct Gap ~2eV
➡ Dresselhaus spin-orbit

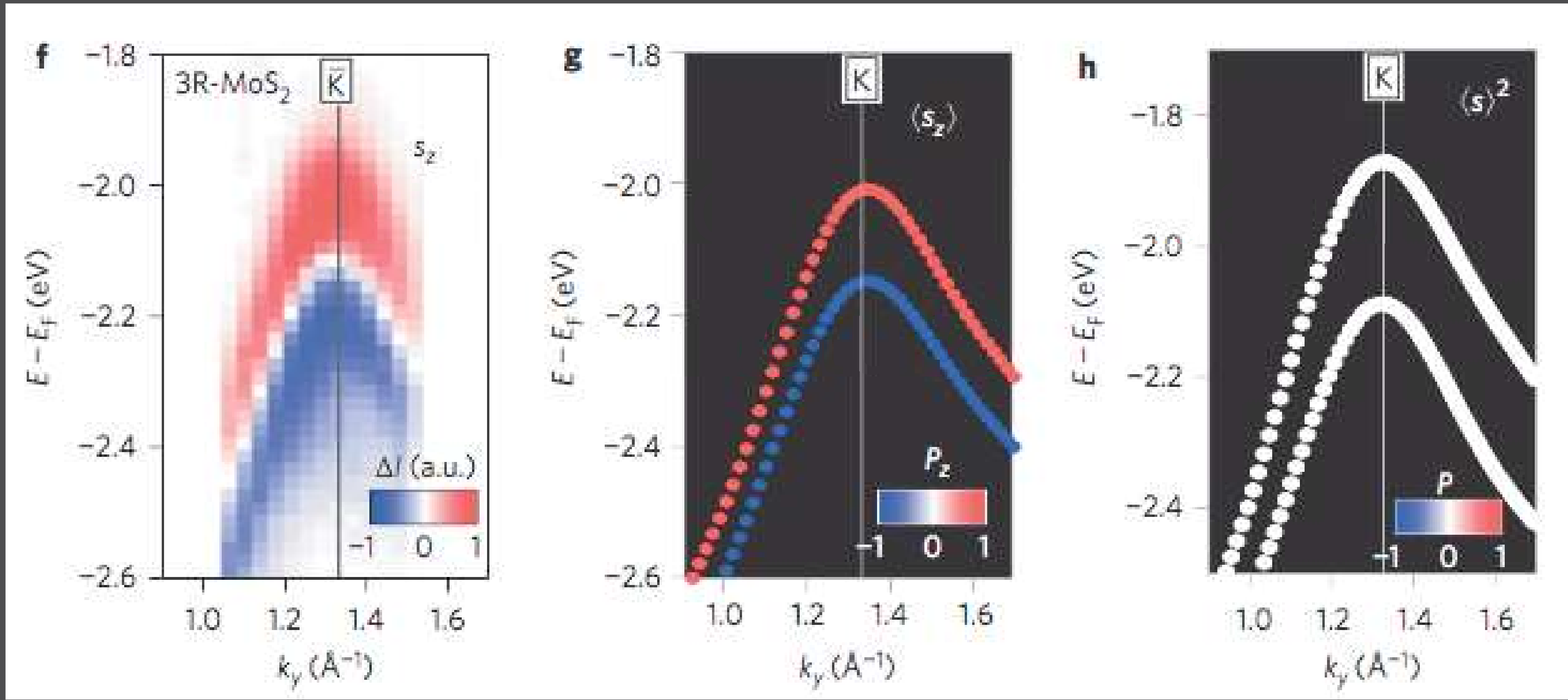
Band-selective spin-splitting

- Partially filled crystal-field-split d-bands
  - Conduction band $|d_{z^2}\rangle$: l_z=0
  - Valence band $\frac{1}{\sqrt{2}}(|d_{x^2-y^2}\rangle \mp i|d_{xy}\rangle)$: l_z= ∓1

- Spin-orbit coupling $\vec{L} \cdot \vec{S}$

150~460meV

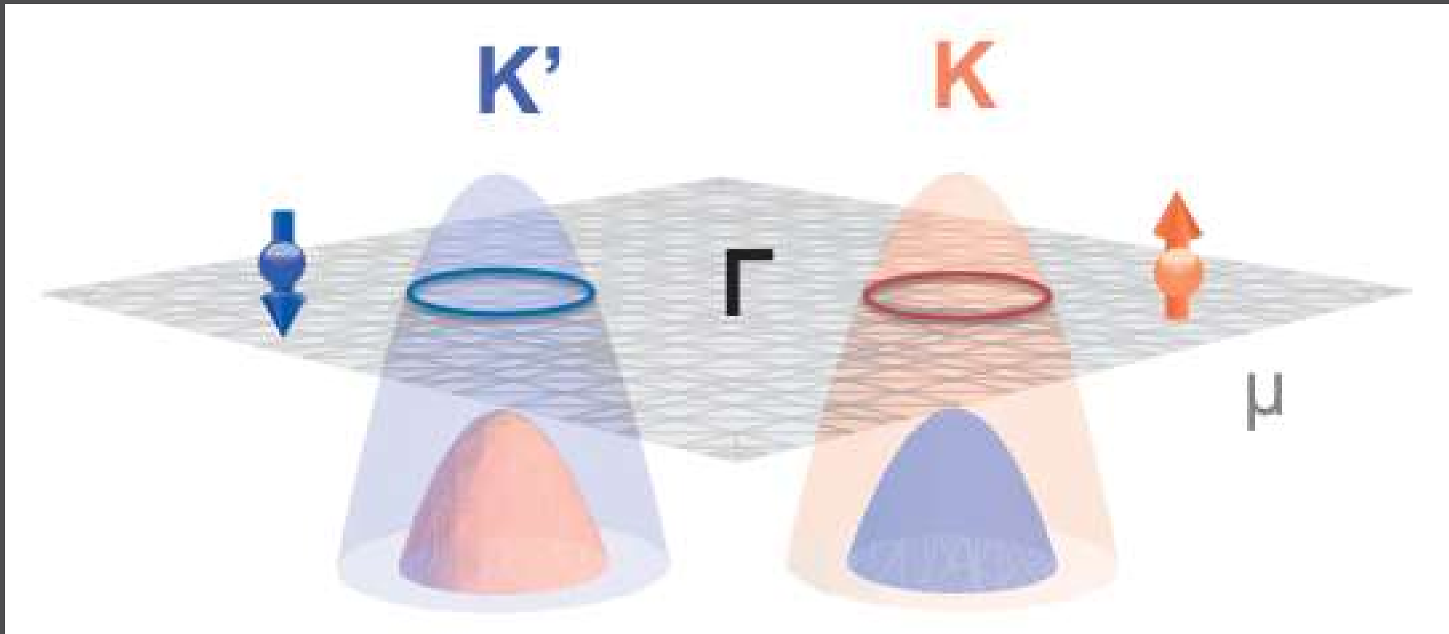




Iwasa group N. Nano (2014)

k-space spin-split FS?

p-doped group VI- TMD!

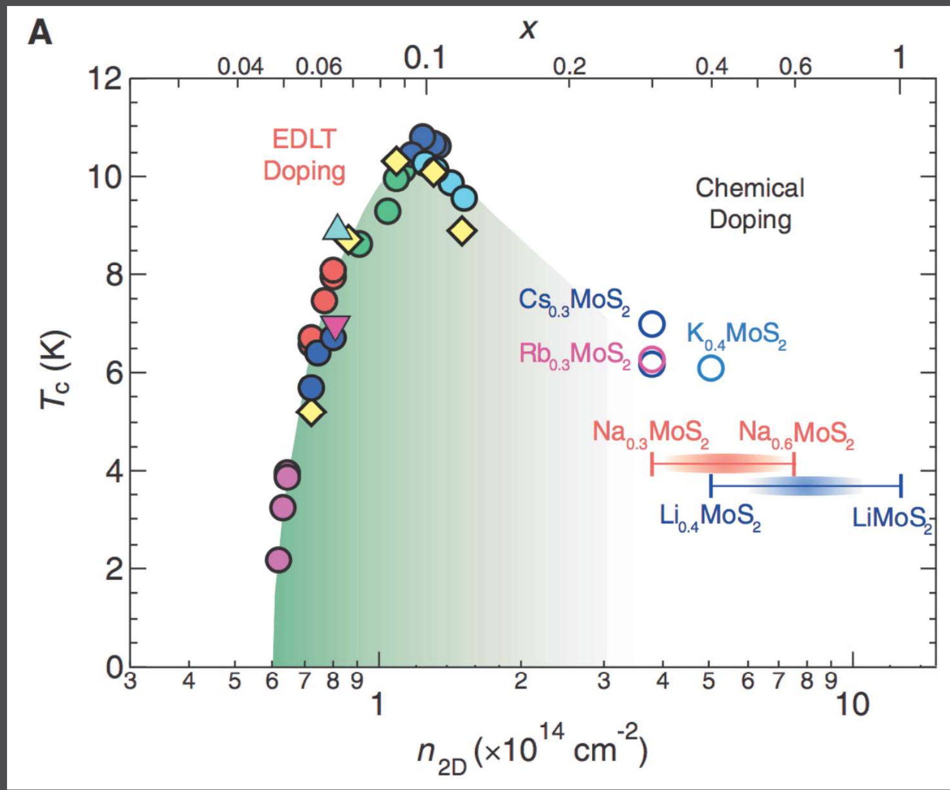


Juice for superconductivity?

- d electrons => expect correlation effects

- n-doped

J.T.Ye et al. (Science 2012)



p-doped TMD

k-space spin-split Fermi surfaces

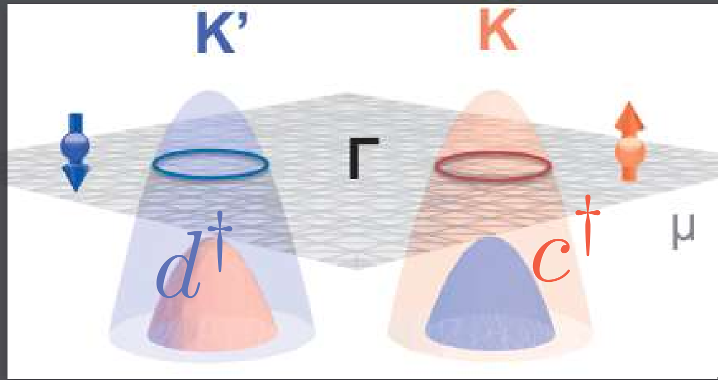
+

Moderate correlation (d-electron)

↓

Topological SC?

Model



- Kinetic term

$$H_0(\vec{q}) = \sum_{\vec{q}} \epsilon(\vec{q})(c^\dagger_{\vec{q}} c_{\vec{q}} + d^\dagger_{\vec{q}} d_{\vec{q}})$$

- Repulsive interaction term

$$H'(W) = \sum_i U n_{i,\uparrow} n_{i,\downarrow}$$

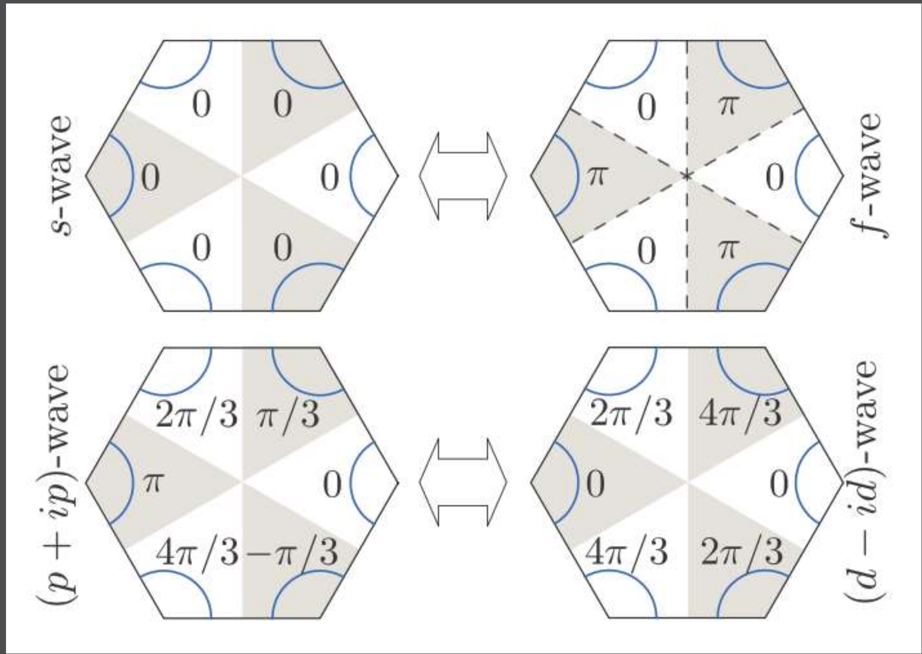
- Point group C3v

Implication of spin-valley locking

- Irrep's of C3v (with full gap)

A1

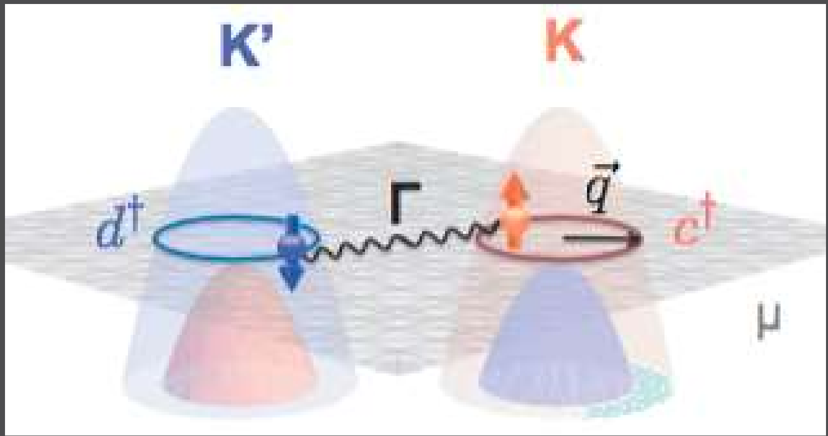
E



- If s-wave is blocked, f-wave is blocked!!

Two possibilities

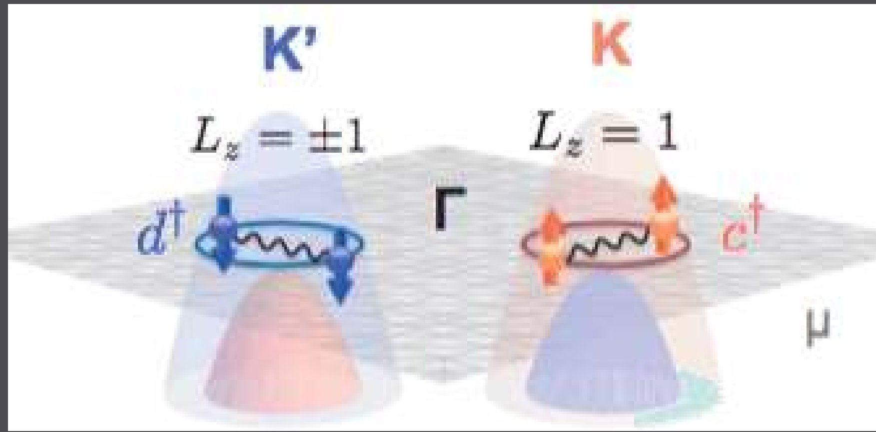
- Intra-pocket p+ip



-T-breaking

- C=2

- Inter-pocket p'wave



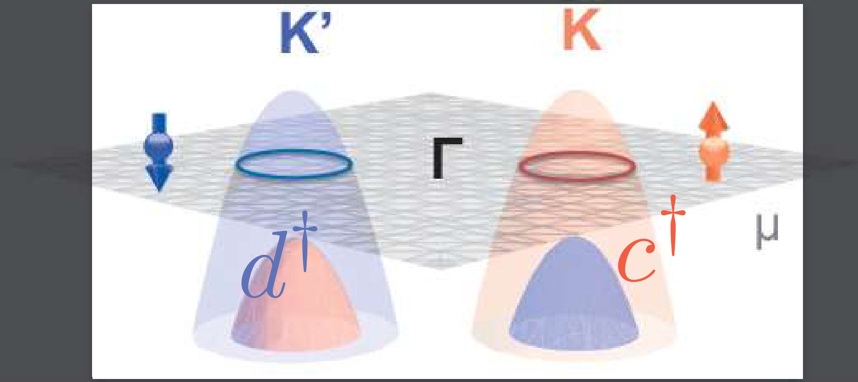
-Modulated

-C=\pm 1 per pocket

Two-step RG on p-doped TMD

Following Raghu, Kivelson, Scalapino (PRB 2010)

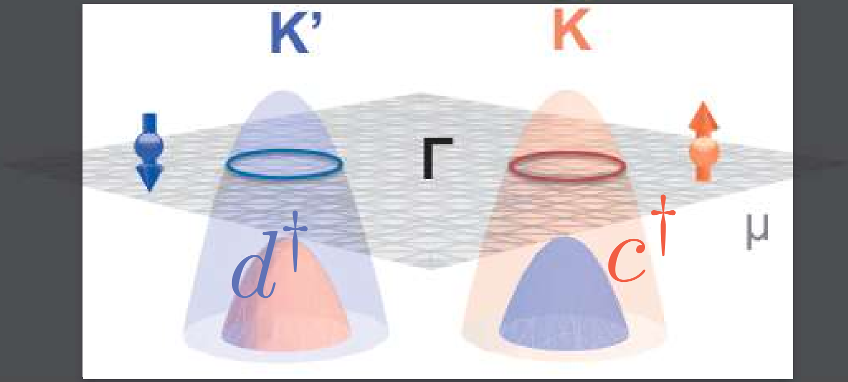
Step I: W -> Λ_0

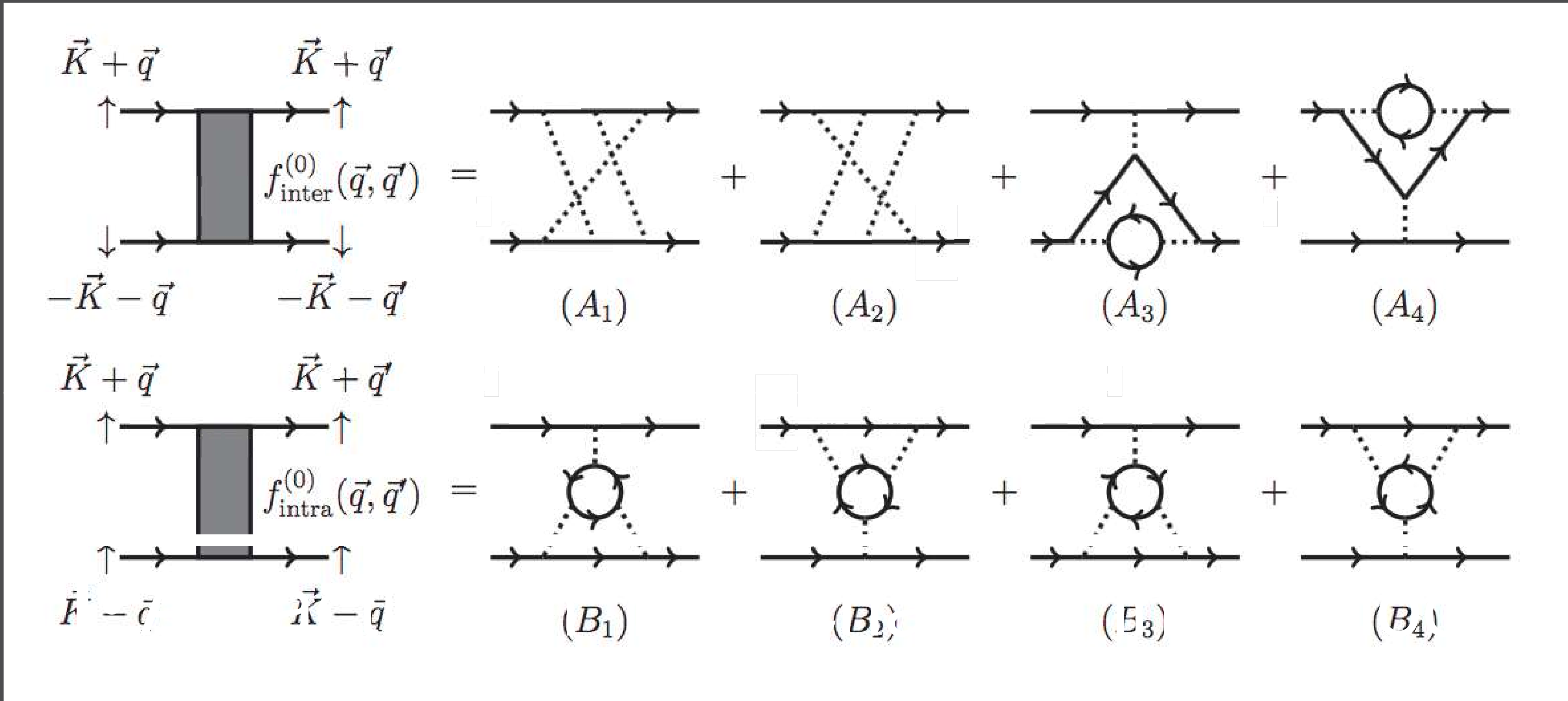


- At scale W: Microscopic model
- At scale Λ_0: Effective model

$$H'_{eff}(\Lambda_0) = \sum_{\vec{q},\vec{q}'}{}' g^{(0)}_{\text{inter}}(\vec{q},\vec{q}')c^\dagger_{\vec{q}'}d^\dagger_{-\vec{q}'}d_{-\vec{q}}c_{\vec{q}} + g^{(0)}_{\text{intra}}(\vec{q},\vec{q}')d^\dagger_{\vec{q}'}d^\dagger_{-\vec{q}'}d_{-\vec{q}}d_{\vec{q}} + (c \leftrightarrow d)$$

Step I: W -> Λ_0

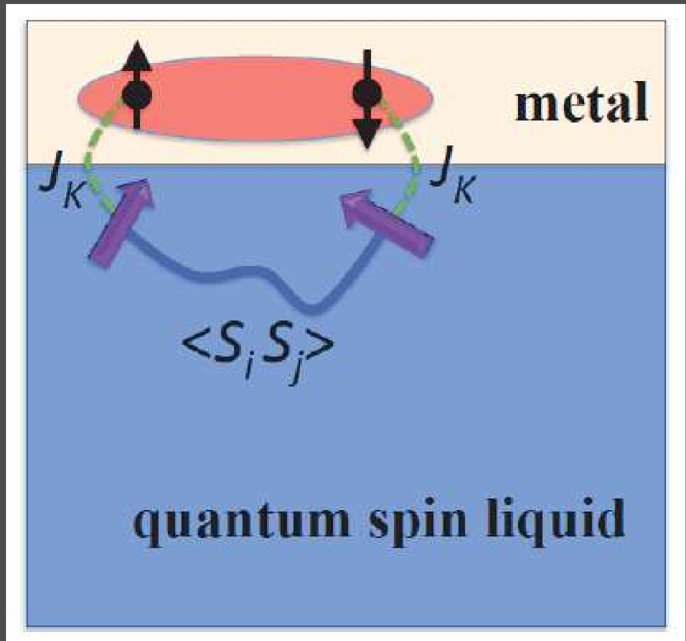




Strategy II

- Manipulate the pairing interaction: target non-phononic mechanism

Topological Superconductivity in Metal/ Quantum-Spin-Ice Heterostructures

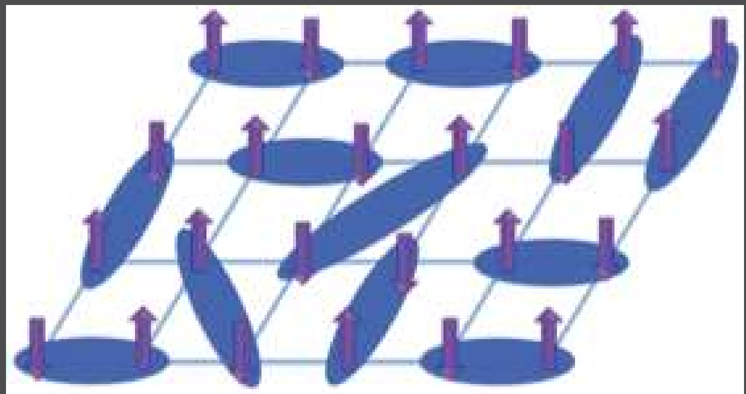


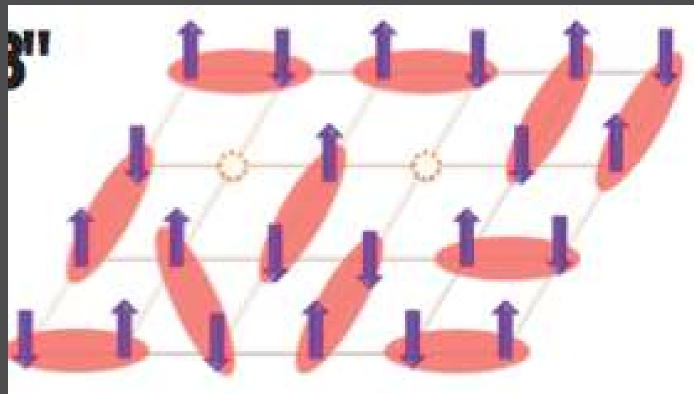
Jian-Huang She, Choonghyun Kim, Craig Fennie, Michael Lawler, E-AK (npj Quantum Materials 2 (1), 64 (2017))

Wanted: non-phononic mechanism

Dope a Quantum spin liquid

P.W.Anderson



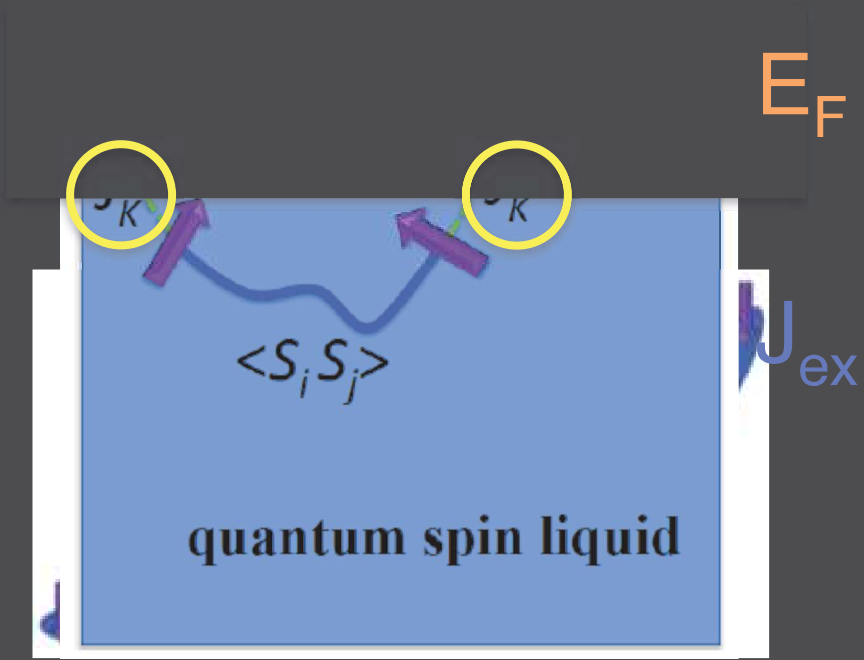


RVB singlet

Cooper pair singlet

Wanted: non-phononic mechanism

Use Quantum paramagnet



- Characteristic energy scales:

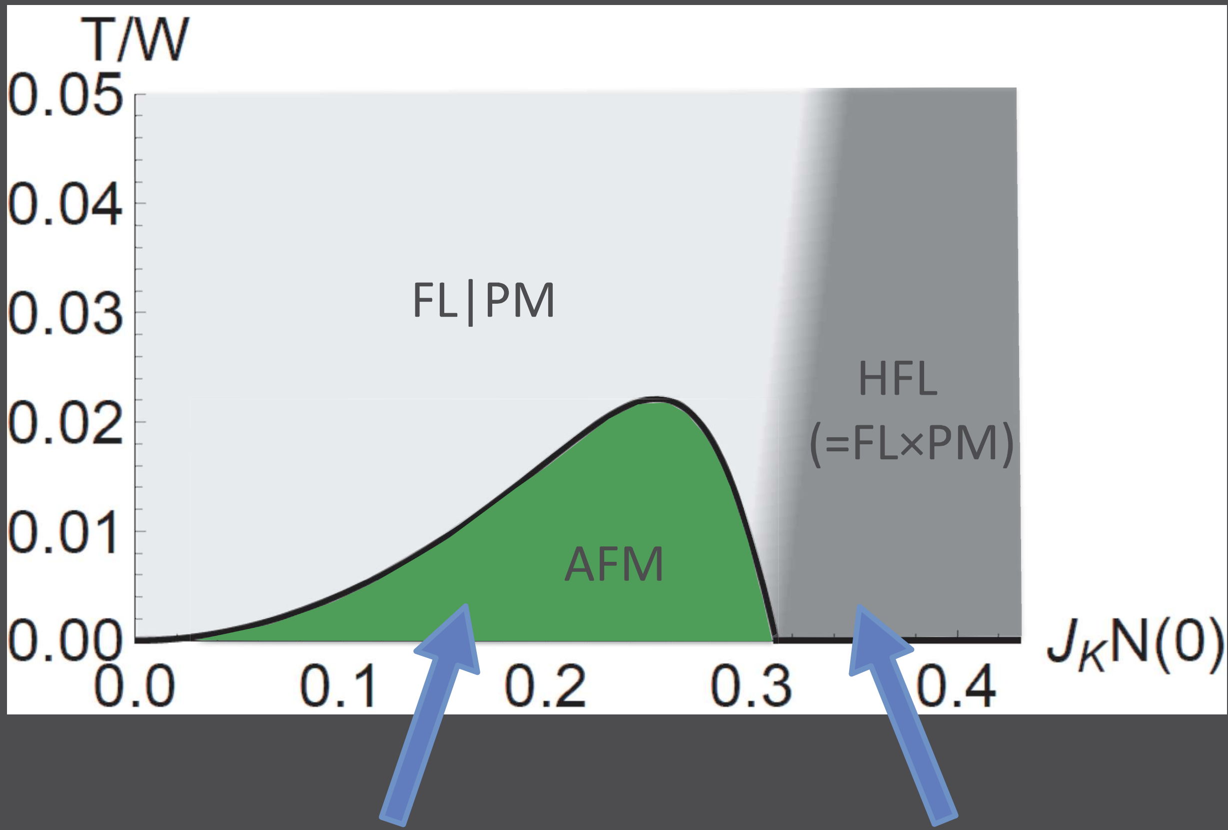
  $E_{F,}\ J_{ex,}\ J_K$

- Perturbative limit:

  $J_K / E_F << 1$

- Spin-fermion model

Spin-fermion model for J_{ex}=0



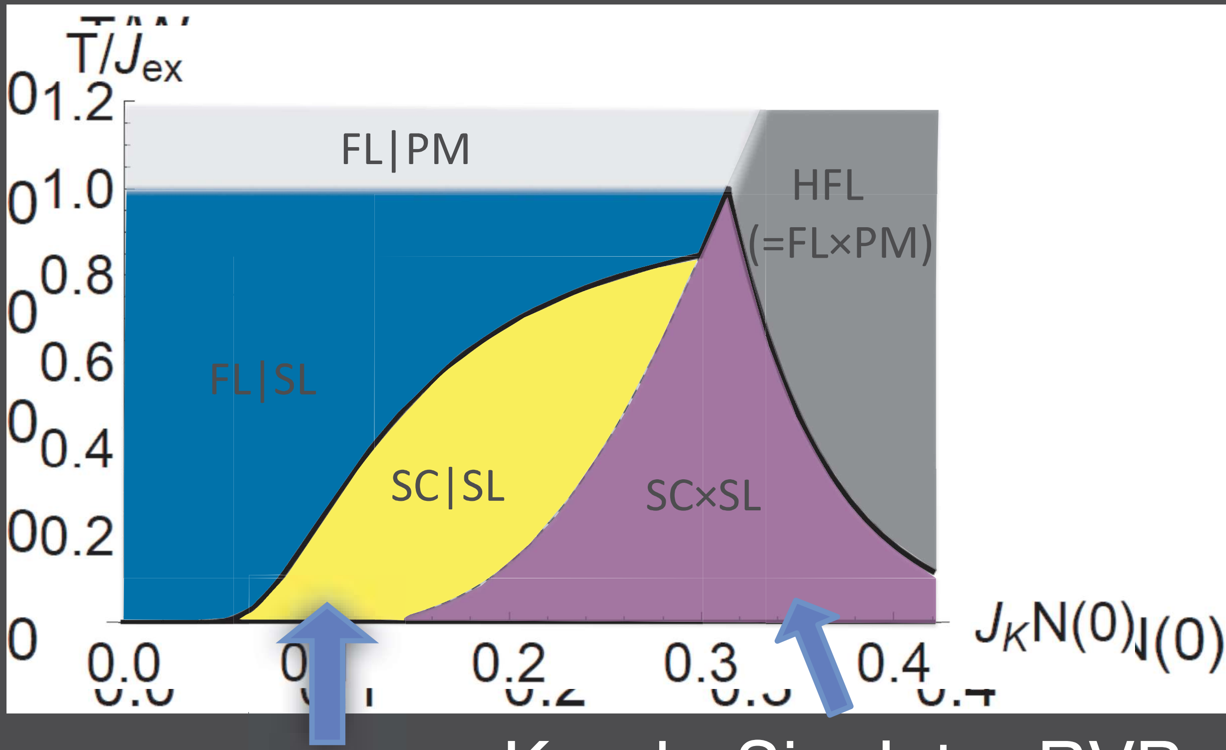
RKKY interaction

Kondo-Singlet

Doniach (1977)

Spin-fermion model for J_{ex}+ Frustration

For $J_{RKKY} \sim J_K^2 N(0) < J_{ex}$ no AFM



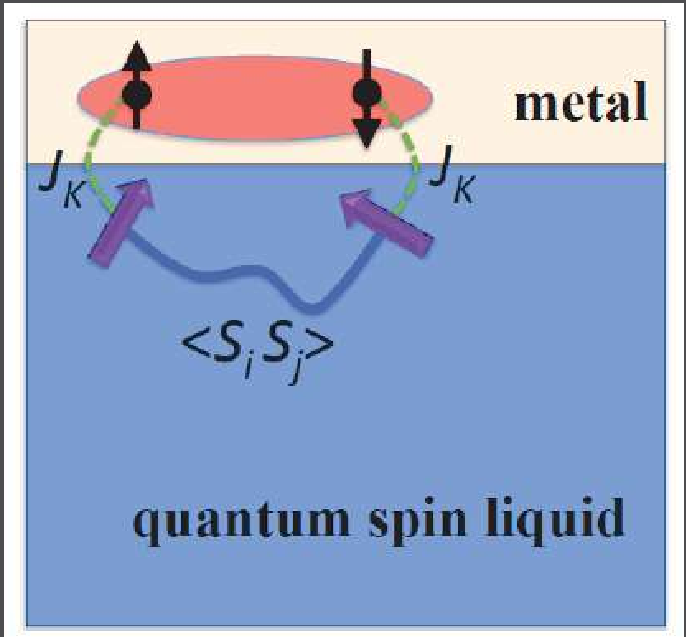
SC "riding" on QSL

Kondo-Singlet + RVB singlet+Cooper pair

Coleman & Andrei (1989)

Senthil, Vojta, Sachdev (2003)

How to predictively materialize SCIQPM ?

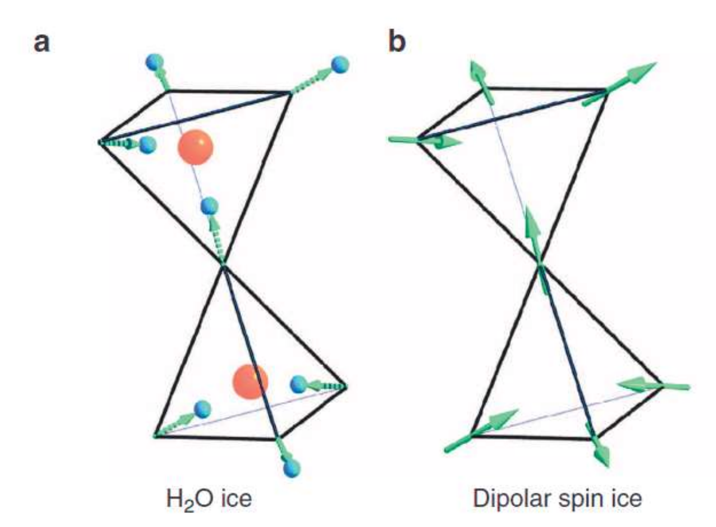


Simple isotropic metal

1. $\langle S \rangle = 0$
2. Dynamic spin fluctuation $\langle S_i S_j \rangle$
3. Well understood

➡ Quantum Spin Ice

Emergent Vector Field in Spin Ice



Kimura et al (2013)

- 2-in 2-out ice rule

$$\nabla \cdot \vec{S}(\boldsymbol{r}) = 0$$

$$\vec{S}(\boldsymbol{r}) = \nabla \times \vec{A}(\boldsymbol{r})$$

- Vector Field Propagator

$$\langle A_a(\boldsymbol{q}) A_b(-\boldsymbol{q}) \rangle \sim \frac{1}{q^2} \left(\delta_{ab} - 2\hat{q}_a \hat{q}_b \right)$$

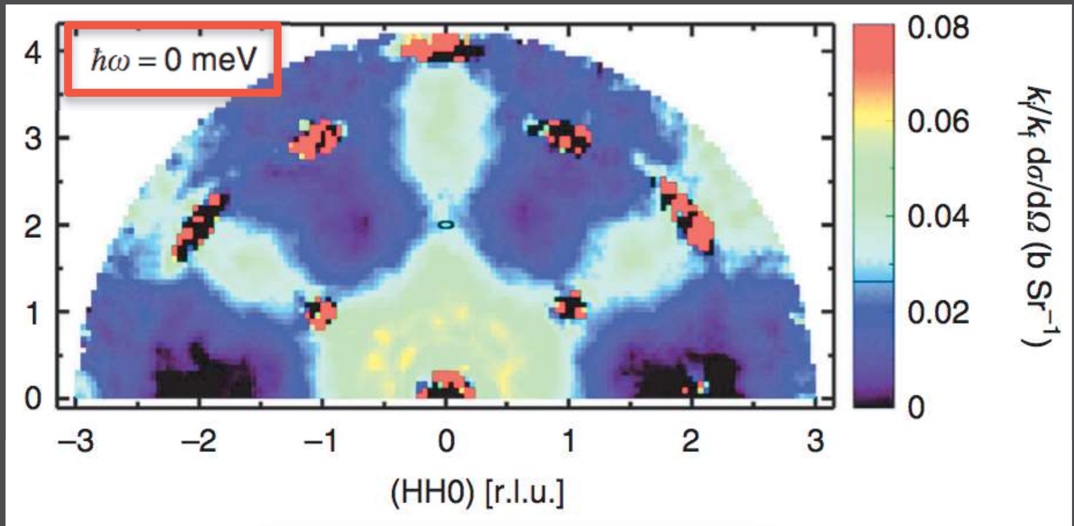
- Spin-spin correlation

$$\langle S_a(\boldsymbol{q}) S_b(-\boldsymbol{q}) \rangle \sim \delta_{ab} - \hat{q}_a \hat{q}_b$$

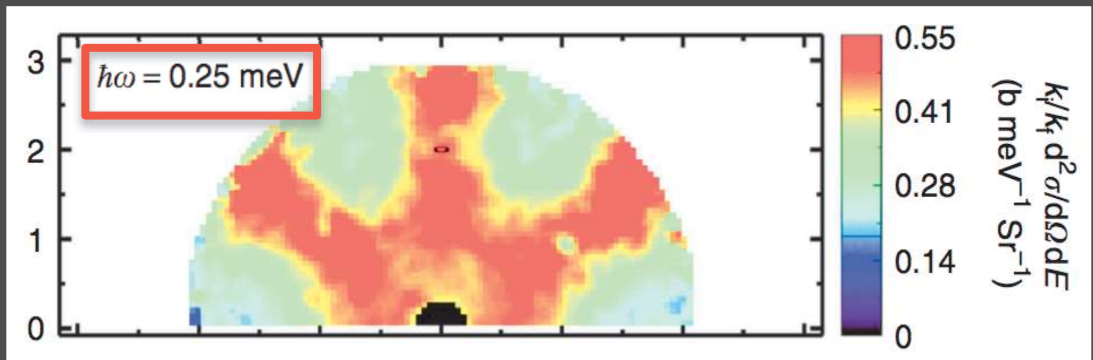
Received 20 Sep 2012 | Accepted 18 Apr 2013 | Published 17 Jun 2013 DOI: 10.1038/ncomms2914

Quantum fluctuations in spin-ice-like $Pr_2Zr_2O_7$

K. Kimura[1], S. Nakatsuji[1,2], J.-J. Wen[3], C. Broholm[3,4,5], M.B. Stone[5], E. Nishibori[6] & H. Sawa[6]



- Elastic neutron: pinch points (spin-ice like)



- Inelastic neutron: over 90% weight

Received 20 Sep 2012 | Accepted 18 Apr 2013 | Published 17 Jun 2013
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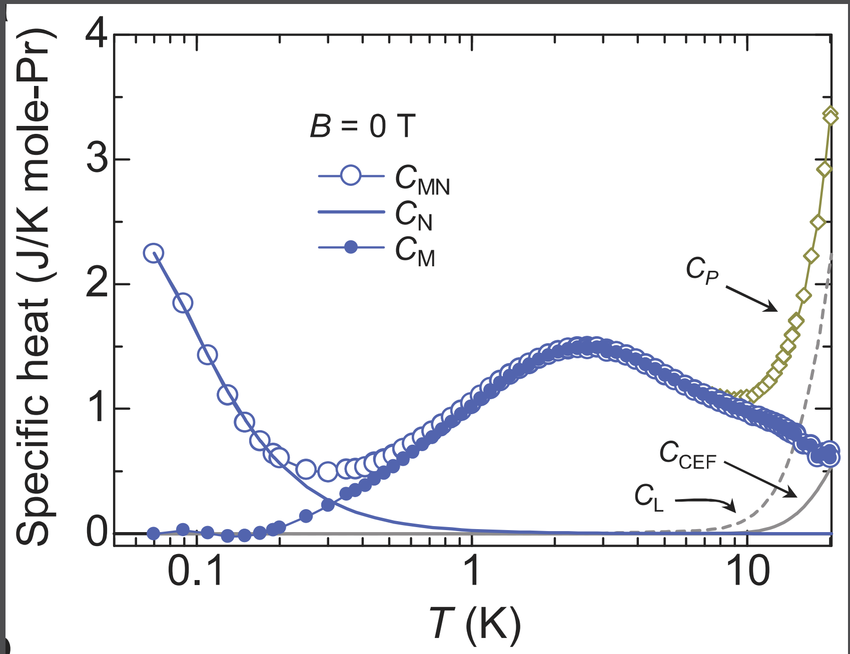
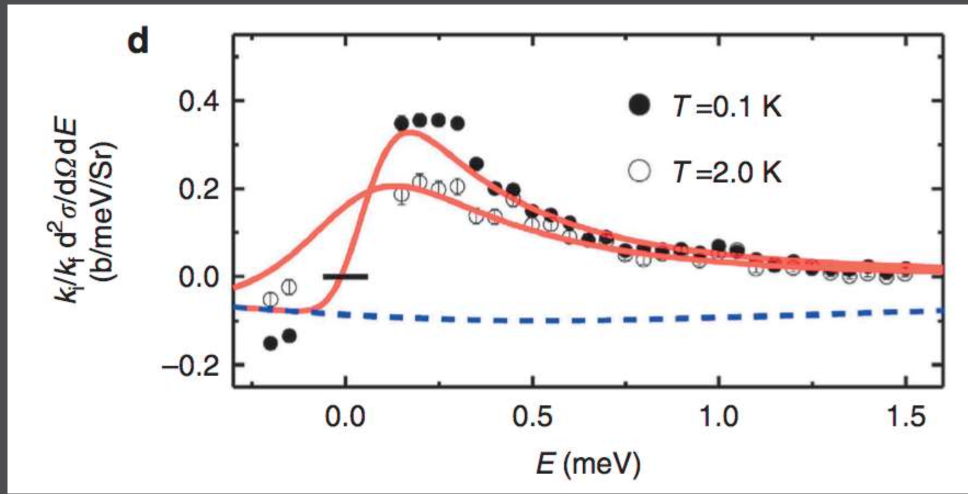
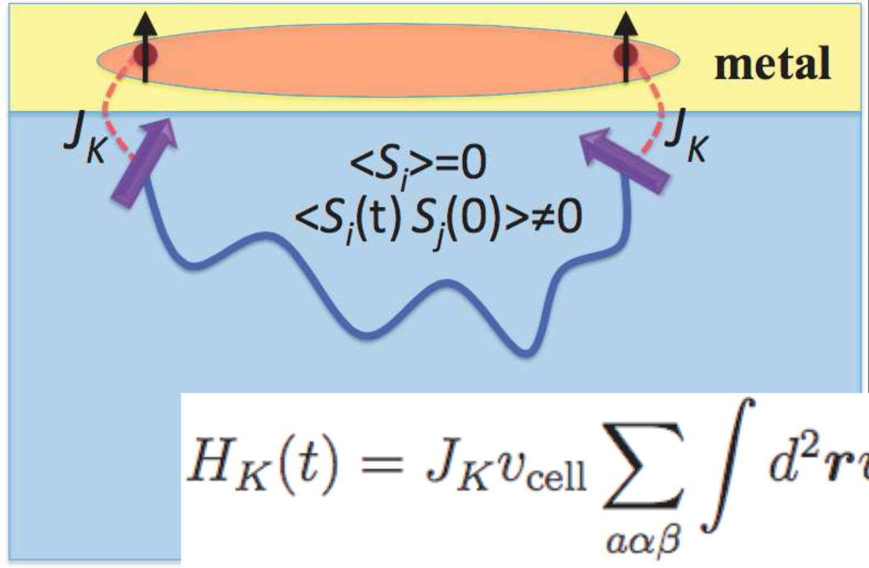




- No order down to 20mK
- Spin fluctuation scale ω_S=0.17meV

Effective Continuum Theory



$$H_c = \sum_{\boldsymbol{k}\alpha} \left(\frac{\hbar^2 k^2}{2m} - E_F \right) \psi^\dagger_\alpha(\boldsymbol{k})\psi_\alpha(\boldsymbol{k})$$

$$H_K(t) = J_K v_{\text{cell}} \sum_{a\alpha\beta} \int d^2\boldsymbol{r} \psi^\dagger_\alpha(\boldsymbol{r}) \sigma^a_{\alpha\beta} \psi_\beta(\boldsymbol{r}) S_a(\boldsymbol{r}_\perp = \boldsymbol{r}, z = 0, t)$$

- Integrate out spins >> Effective e-e interaction

$$H_{\text{int}}(t) = -(J_K^2 v_{\text{cell}}^2 / 2\hbar) \sum_{ab} \int dt' \int d^2\boldsymbol{r} d^2\boldsymbol{r}' s_a(\boldsymbol{r}, t) \langle S_a(\boldsymbol{r}, 0, t) S_b(\boldsymbol{r}', 0, t') \rangle s_b(\boldsymbol{r}', t')$$

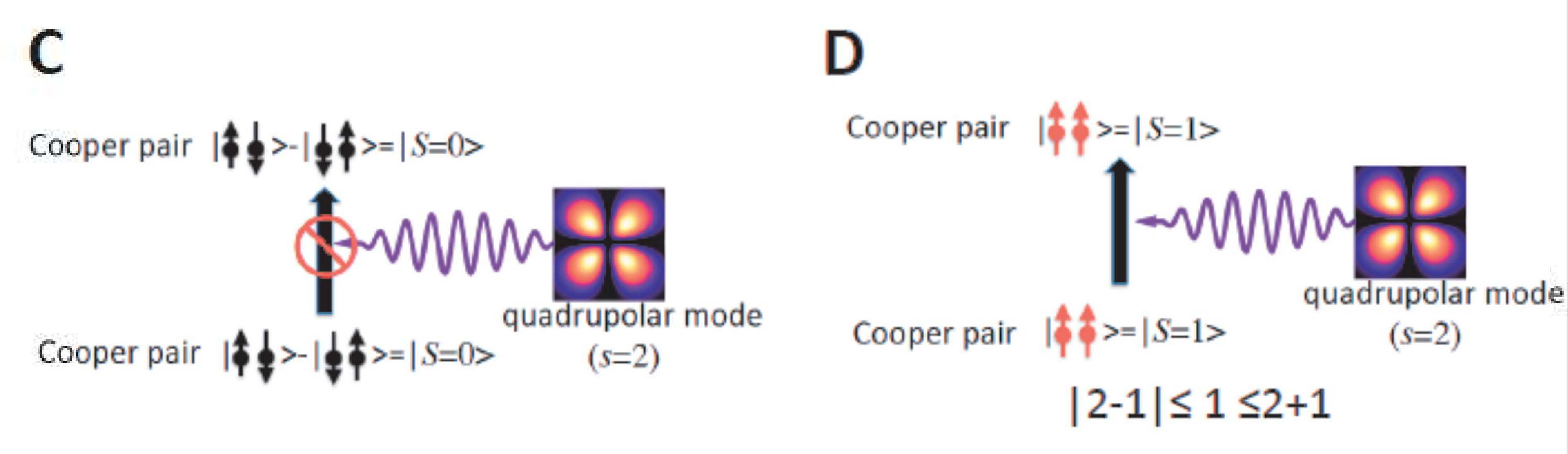
$$s_a(\boldsymbol{r}, t) = \sum_{\alpha\beta} \psi^\dagger_\alpha(\boldsymbol{r}, t) \sigma^a_{\alpha\beta} \psi_\beta(\boldsymbol{r}, t)$$

Selection Rule Dictated Odd-Parity

- Pair binding problem with dipole-dipole interaction

$$V_{\mathrm{dd}} = \frac{1}{r^3}[\vec{S}_1 \cdot \vec{S}_2 - 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r})] \propto \mathcal{R}^{(2)}(r_1, r_2) \cdot \mathcal{S}^{(2)}(s_1, s_2)$$

- Wigner-Eckart thm: $\langle l' | \mathcal{T}^{(r)} | l \rangle = 0$ unless $|r - l| \leq l' \leq (r + l)$

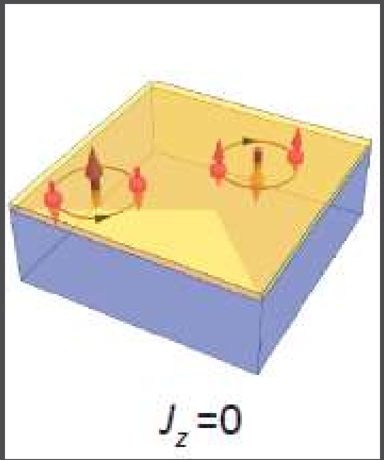


Dealing with interacting electrons?

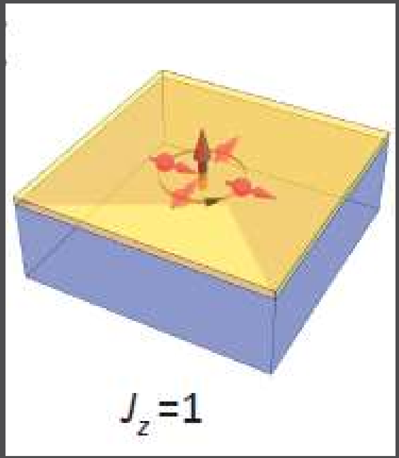
$$H_{\rm int}(t) = -(J_K^2 v_{\rm cell}^2/2\hbar)\sum_{ab}\int dt'\int d^2\boldsymbol{r}d^2\boldsymbol{r}' s_a(\boldsymbol{r},t)\langle S_a(\boldsymbol{r},0,t)S_b(\boldsymbol{r}',0,t')\rangle s_b(\boldsymbol{r}',t')$$

- Separation of scale: $\omega_S/E_F \ll 1$
  ➡"Migdal theorem"
- Dimensionless ratio: $\lambda \sim N(0)V \sim J_K^2 N(0)/J_{\rm ex} < 1$
- Full problem ≈
  solving the BCS mean-field theory $T_c \sim \omega_s e^{-1/\lambda}$

Leading channels



$$(k_x + ik_y)| \downarrow\downarrow\rangle + (k_x - ik_y)| \uparrow\uparrow\rangle$$



$$(k_x \pm ik_y)\frac{| \uparrow\downarrow\rangle + | \downarrow\uparrow\rangle}{\sqrt{2}}$$